**Titel:** **Method for calibrating a camera-laser-unit in respect to a calibration-object**

## Specification

The present invention refers to a method for calibrating a camera-laser-unit in respect to at least one calibration-object disposed at a given position and orientation in a three-dimensional space. The camera-laser-unit comprises at least one laser (light-amplification by stimulated emission of radiation) and at least one camera. The laser and the camera are disposed in a given distance to one another. An optical axis of the laser and an optical axis of the camera include a given angle. The camera-laser-unit is adapted to record the location, form and/or dimensions of a measurement-object.

Furthermore, the invention refers to a calibration-object used for calibrating a camera-laser-unit and disposed at a given position and orientation within a three-dimensional space. The camera-laser-unit comprises at least one laser and at least one camera. The laser and the camera are disposed in a given distance and an optical axis of the laser and an optical axis of the camera have a given angle. The camera-

laser-unit is adapted to record the location, form and/or dimensions of a measurement-object.

Camera-laser-units of the kind mentioned above are well known in the state of the art. For example, such a camera-laser-unit is produced and sold by Perceptron, Inc., 47827 Halyard Drive, Plymouth, MI 48170, USA. Furthermore, such a camera-laser-unit and the use of such a unit is described in detail in the US-patents 4,645,348 and 6,166,811 both issued to Perceptron, Inc. A preferred embodiment of a camera-laser-unit of the kind mentioned above is described in detail in the German patent application 103 11 247, filed on March 14, 2003 by the applicant of the present patent application. The publications of the two US-patents and of the German patent application are all included by reference into the present specification.

According to the methods known in the art, calibration of a camera-laser-unit is very complex and time-consuming. To begin with a first calibration-object has to be disposed in respect to the camera-laser-unit and the camera is calibrated in respect to the first calibration-object by, for example, making use of a Tsai algorithm well known in the state of the art. Thereafter, a second calibration-object has to be disposed in respect to the camera-laser-unit and the laser is calibrated in respect to the second calibration-object, too.

The second calibration-object in the state of the art typically comprises a planar object with an array of pins protruding from the plain. The pins represent a non-coplanar calibration-pattern used for calibrating the laser. The dimensions and distances of the pins are known. The problem is that the pins when illuminated by the laser or any other light source form shadows on the adjacent pins, the shadows rendering very complicated and even impossible an accurate calibration of the laser.

Therefore, it is known to make the pins retractable and to extract them one by one from the plains of the cubic second calibration-object. After the extraction of each pin, a calibration routine is run and then the next pin is extracted with another calibration routine run thereafter, and so on. Thus, the calibration of the laser consists of numerous calibration routines. It may be well understood that in this way calibration of the laser is very cumbersome and requires a relatively long time. Typically, the calibration of the laser with the described method will take a couple of hours. Furthermore, the known calibration-method may be used only in laboratories or other places where the calibration assembly required for the calibration process may be build up. It is certainly not qualified for calibration of lasers during the intended use of the camera-laser-unit.

One way for simplifying the calibration of the laser could be to reduce the number of pins. However, reducing the number of pins would reduce accuracy of the calibration.

It is an object of the present invention to simplify the process of calibration of a camera-laser-unit without reducing the available accuracy.

This object is solved by a method for calibrating a camera-laser-unit comprising the features of claim 1. In particular, a method of the above mentioned kind is suggested comprising the steps of:

- selecting a calibration-object comprising at least two plains disposed in a given angle to each other and provided with a given non-coplanar calibration-pattern;
- disposing the calibration-object in respect to the camera-laser-unit in a given position and orientation in the three-dimensional space, wherein the orientation of the calibration-object is such that light emitted by the laser is visible on at least two plains of the calibration-object;
- calibrating the camera in respect to the calibration-object using a Tsai algorithm;
- activating the laser so it emits light visible on the at least two plains of the calibration-object;
- recording the light on the plains by the camera;

- determining the laser-properties from the light recorded by the camera; and
- calibrating the laser according to the determined laser-properties.

It is a main aspect of the present invention that the same calibration-object is used for the calibration of the camera as well as for the calibration of the laser. Furthermore, after calibration of the camera in respect to the calibration-object, the laser is calibrated in respect to the (already calibrated) camera. With other words, the camera is used for calibrating the laser.

The whole procedure for calibrating a camera-laser-unit takes very little time and can be accomplished within few seconds. This makes it the ideal procedure for calibration of a camera-laser-unit during its intended field use. For example, the application of the camera-laser-unit (recording the location, form and/or dimensions of a measurement-object) could be interrupted for a short period, an industrial robot carrying the camera-laser-unit could move the unit to the calibration-object and dispose it in front of the object. Then the calibration process according to the present invention is run. Thereafter, the robot would move the camera-laser-unit away from the calibration-object back to the measurement-object and the intended use of the unit would be resumed.

According to a preferred embodiment of the invention it is suggested that calibrating the laser comprises the step of defining a relative position and orientation of the laser in respect to a coordinate frame associated with the calibration-object, wherein the coordinate frame associated with the calibration-object is in a given position and orientation in the three-dimensional space.

Concerning the calibration of the laser, it is suggested that

- the light emitted by the laser is visible on the plains of the calibration-object as a line on each plain, the lines intersecting on a contact line of the two plains; and
- the laser-properties are determined from the lines recorded by the camera by means of a line detection algorithm.

Visible in the sense of the present invention means that the light emitted by the laser is visible to the camera. So this definition would comprise, for example, a case where the laser emits infrared (IR) light, invisible to the human eye but visible to an IR camera.

In other words, three points can be defined for the calibration of the laser, the two end points of the lines on the two plains of the calibration-object and the point of intersection of the two lines.

Further, it is suggested that

- the light emitted by the laser is visible on the plains of the calibration-object as a line on each plain, the lines intersecting on a contact line of the two plains;
- a laser-plain is defined by the optical axis of the laser and the lines visible on the plains of the calibration-object; and
- in order to calibrate the laser according to the determined laser-properties, the position and orientation of the laser-plains in respect to a coordinate frame associated with the calibration-object is defined.

Concerning the calibration of the camera it is suggested that the method comprises the step of defining a relative position and orientation of the camera in respect to a coordinate frame associated with the calibration-object, wherein the coordinate frame associated with the calibration-object is in a given position and orientation in the three-dimensional space.

According to another embodiment of the present invention, it is suggested that a transformation matrix is defined depending on the relative position and orientation of the camera in respect to a coordinate frame associated with the

calibration-object, the relative position and orientation of the laser in respect to a coordinate frame associated with the calibration-object, and optionally on internal camera parameters. The picture taken from the measurement-object by the camera is superposed or multiplied with the transformation matrix in order to obtain the actual location, form and/or dimensions of the measurement-object.

According to yet another embodiment of the present invention, it is suggested that the camera-laser-unit to be calibrated is grasped by an industrial robot and disposed in respect to the calibration-object in a given position and orientation in the three-dimensional space, wherein the orientation of the camera-laser-unit is such that light emitted by the laser is visible on at least two plains of the calibration-object.

Furthermore, the object of the present invention is solved by a calibration-object of the above-mentioned kind characterized in that it comprises two plains disposed in a given angle to each other, provided with a non-coplanar calibration-pattern on each plain comprising an array of features, and the calibration-object used for calibration of the camera as well as for calibration of the laser. The array of features represents a grid of calibration points used for calibrating the camera as well as the laser of the camera-laser-unit.

According to a preferred embodiment of the present invention it is suggested that the angle between the two plains is a right angle. The light emitted by the laser is visible on the plains of the calibration-object as a line on each plain, the lines intersecting on a contact line of the two plains. In this way the maximum possible volume in space can be calibrated.

The features of the calibration-object may comprise recesses, in particular cavities with a circular cross section, or prints on the plains of the calibration-object. The features may have any shape or design. For example, the features may comprise rectangular recesses or prints with a square or a circular cross section viewed from above. The prints on the plains have a different color or a different surface than the plains of the calibration-object, so the features and the calibration pattern can be detected by the camera during the calibration process.

Further embodiments as well as further advantages of the present invention are outlined in the following description of the enclosed figures.

Fig. 1 shows a schematic view of a preferred embodiment of a calibration setup for calibrating a camera-laser-unit according to the present invention;

Fig. 2 shows a schematic view of a preferred embodiment of an assembly for recording the location, form and/or dimensions of a measurement-object by means of the calibrated camera-laser-unit;

Fig. 3 shows a calibration setup for the camera-laser-unit in detail;

Fig. 4 shows a flow chart of a preferred embodiment of a method for calibrating a camera-laser-unit according to the present invention; and

Fig. 5 shows an example for a calibration-image.

The present invention refers to a camera-laser-unit for recording the location, form and/or dimensions of a measurement-object. The camera-laser-unit shown in figure 2 as a whole is designated with reference sign 1. It comprises mounting means 2 with a camera 3 and a light source 4, in particular a laser, mounted thereon. The laser 4 illuminates part of the measurement-object 5 and the camera 3 takes an image of the illuminated measurement-object 5. The camera 3 comprises a CCD (charged coupled device)-chip 6 or other means (e.g. a CMOS-chip) for converting optical signals of the image into electrical signals for further processing within the camera-laser-unit 1. Furthermore, the camera 3 comprises an optical system 7, in particular a lens, for

reproducing the image on the CCD-chip 6. The camera 3 and the laser 4 are disposed on the mounting means 2 such that an optical axis 8 of the camera 3 intersects an optical axis 9 of the laser 4 at a measurement point 10. The measurement point 10 is not necessarily disposed on a contact line between the two plains 14, 15. Preferably the optical axis 8 and 9 are disposed in an angle $\alpha$ of 45° in respect to one another. The laser 4 generates a line 11 on the measurement object 5, which is recorded by the camera 3 and reproduced on the CCD-chip 6 by the lens 7.

For example, a camera-laser-unit of the mentioned kind is produced and sold by Perceptron, Inc., 47827 Halyard Drive, Plymouth, MI 48170, USA. Furthermore, such a camera-laser-unit and the use of such a unit is described in detail in the US-patents 4,645,348 and 6,166,811 both issued to Perceptron, Inc. A preferred embodiment of a camera-laser-unit of the kind mentioned above is described in detail in the German patent application 103 11 247, filed on March 14, 2003 by the applicant of the present patent application. The publications of the two US-patents and of the German patent application are all included by reference into the present specification, in particular for more detailed information on possible structures of camera-laser-units and on the process of determining the location, form and/or dimensions of a measurement-object by means of a camera-laser-unit.

However, before the camera-laser-unit 1 can be used for recording the location, form and/or dimensions of a measurement-object 5, it has to be calibrated. During the calibration process the camera 3 and the laser 4 are put into relationship with the coordinates of a calibration-object 12 (see figure 1) and a three-dimensional space 13, if the calibration-object 12 is disposed at a given position and orientation within the three-dimensional space 13. In particular, camera parameters are determined and a relative position of one or more laser plains is defined with respect to a coordinate frame 19 related to the calibration-object 12. A laser plain is defined by the optical axis 9 and the line 11 of light emitted by the laser 4 (see figure 2 or 3). Calibration of the camera-laser-unit 1 is necessary in order to allow the camera-laser-unit 1 to determine absolute values for the location, form and/or dimensions of the measurement-object 5.

Figure 3 shows the calibration-object 12 according to the present invention with its two plains 14, 15 facing the camera-laser-unit 1. Any object 12 comprising two calibration plains 14, 15 is suitable for the calibration process according to the invention. A non-coplanar calibration-pattern comprising an array of recesses 17 is disposed on the two plains 14, 15. Of course, the calibration-object 12 can comprise an array of any kind of features, such as simple

prints on the plains 14, 15 of any desired shape and cross section, instead of the recesses 17.

In the embodiment shown in figure 3 the calibration-pattern comprises a six by six array of 36 grid-like disposed recesses 17 on each plain 14, 15. Each recess 17 of the calibration-pattern is designed as a cavity having a circular cross section viewed from above. The same calibration-object 12 is used for calibration of the camera 3 as well as for calibration of the laser 4. The two plains 14, 15 are disposed in a known angle β, preferably 90°. The closer to perpendicular the two plains 14, 15 are, the larger is the volume over which the calibration is valid, so larger angles β could be used if volume is not a critical factor.

The present invention refers to a particularly advantageous process for calibrating the camera-laser-unit 1 in respect to the calibration-object 12 disposed at a given position and orientation within the three-dimensional space 13. The process comprises the following steps:

- Selecting a calibration-object 12 comprising at least two plains 14, 15 disposed in a given angle β to each other and provided with a given non-coplanar calibration-pattern (see figure 3). Preferably, the angle β is 90°.

- Disposing the calibration-object 12 in respect to the camera-laser-unit 1 in a given position and orientation in the three-dimensional space 13, wherein the orientation of the calibration-object 12 is such that light emitted by the laser 4 is visible for the camera 3 on at least two plains 14, 15 of the calibration-object 12.
- In a first step, calibrating the camera 3 in respect to the calibration-object 12 using a Tsai algorithm. The Tsai algorithm is well known for camera calibration. It is described in detail in M. Tapper, Ph. J. McKerrow, J. Abrantes: "Problems Encountered in the Implementation of Tsai's Algorithm for Camera Calibration", Proc. 2002 Australasian Conference on Robotics and Automation, Auckland, 27-29 November 2002. Concerning the camera calibration by means of a Tsai algorithm reference is made to this document.
- In a second step calibrating the laser 4 in respect to the (already calibrated) camera 3, and activating the laser 4 in order to make it emit light (line 11) visible as two lines 11a, 11b on the two plains 14, 15 of the calibration-object 12,
- recording the light (lines 11a, 11b) on the plains 14, 15 by the camera 3 and reproducing the image (lines 16a, 16b) on the CCD-chip 6 by the camera lens 7,

- determining the laser-properties from the light 16 recorded by the camera 3, and
- calibrating the laser 4 according to the determined laser-properties.

The laser-properties are determined from the properties (length and angle $\gamma$) of the lines 16a, 16b reproduced on the CCD-chip 6 of the already calibrated camera 3 by using a line detection algorithm. The two lines 11a, 11b can be easily reconstructed in space from the images 16a, 16b using the camera parameters and the known geometry of the calibration object 12. Once the two three dimensional lines 11a, 11b are determined, the information is adequate to reconstruct the laser plain(s).

According to the present invention, calibration of the camera-laser-unit 1 is performed in two steps:

- First, standard camera calibration is performed to define the internal parameters of the camera 3 and the position of the camera 3 with reference to a coordinate system.
- Second, the position of the laser plain (defined by the optical axis 9 and the line 11) is defined with reference to the same coordinate system.

These two sets of parameters - camera parameters and laser plain equations - provide all the information necessary for

performing projection and reconstruction using the camera-laser-unit 1 (e.g. transformation from image pixels 18 of the CCD-chip 5 (see figure 3) into millimeters (mm) and vice versa.

Making reference to the flow chart of figure 4, the method for calibrating the camera-laser-unit 1 according to the present invention will now be described in detail. The first step of the calibration process is to calibrate the camera 3 (step 20) using an image 21 and the geometry 22 of the calibration object 12 and nominal camera parameters 23. The calibration of the camera is done by using a non-coplanar Tsai calibration algorithm. As a result of the camera calibration the camera parameters 24 are obtained.

The second step of the calibration process is to determine the laser plain(s) (step 25) defined by the optical axis 9 and the line 11 of light emitted by the laser 4. This can be accomplished by detecting the points belonging to the laser lines 11a, 11b visible on the calibration-object 12. The laser line(s) 11a, 11b are extracted (step 26) from the laser line image 27 taken by the camera 3. The geometry 22 of the calibration object 12, the camera parameters 24 and the extracted laser lines 26 are used for determining the laser plain(s) 25. As a result of the determination of the laser plains(s) the laser plain(s) 28 are obtained. Output 29 is calculated from the camera parameters 24 and the laser

plain(s) 28. The output is, for example, a transformation matrix.

Figure 5 shows an example for a calibration-image comprising two laser plains each with lines 11a and 11b on the plains 14 and 15 of the calibration object 12 respectively. Provided that the scene illumination is not too bright (to avoid saturation) and that the surface of the calibration object 12 is not too reflective, the laser lines 11a and 11b can be easily distinguished.

The detection of the laser lines 11a and 11b comprises the following steps:

- Automatically defining or detecting the regions in the image recorded by the camera 3 covered by each plain 14, 15;
- For each region:
  - o scanning the region horizontally or vertically, depending on the relative positions of camera 3 and laser 4 and detecting the brightest pixel along each line or column. For multiple laser plains (see figure 5), multiple points can be detected, provided that some estimation for the minimum and maximum distance between the lines is known (in pixels). This estimation can either be defined by the user, or calculated automatically from the

angle between two adjacent laser plains and the calibration plains' 14, 15 positions.

- For each detected pixel, detecting the center of intensity on its neighbourhood, using the weighted average of pixel intensities.
- For each laser plain, fitting a line on the detected points, using a linear regression algorithm.
- Calculating the distance of each detected point from all detected lines 11a, 11b. If the point is closer to some other line 11a, 11b, then this point is misclassified, so it has to be moved to the correct set of points.

One approach to define a laser plain once a pair of laser lines 11a, 11b has been extracted (step 26), is to reconstruct the lines in three dimensional space, using the camera calibration parameters 24 and the plain equations of the calibration plains 14, 15. The two reconstructed lines have adequate information to determine the plain of the laser 4 in the same coordinate system. A second approach that has proved to be more accurate, is to reconstruct all detected points (using the camera parameters 24 and the equations of the calibration plains 14, 15), and iteratively fitting a plain to the reconstructed set of points, discarding at each step the most distant points. The position and orientation of the two plains 14, 15 can be easily defined with respect to a

common coordinate system, e.g. centered at the point of intersection 10 of the two lines 11a, 11b.

As described above, calibration of a camera-laser-unit 1 with any number of laser plains can be performed using a three dimensional calibration-object 12, comprising at least two calibration plains 14, 15. Of course, the complexity of the procedure would increase if objects 12 with more than two plains were considered. The main advantages of the method according to the present invention are:

- The same camera model that is used for the calibration of the camera 3 can be used for the calibration of the laser 4 allowing a straight forward integration of the laser calibration into existing camera calibration processes.
- Calibration of the camera 3 is performed by using an already existing, well known and highly tested Tsai-based algorithm and appropriate software.
- The topology of the calibration-object 12 is easy to construct with very high accuracy.
- High accuracy of calibration can be guaranteed over an entire volume covered by the calibration object 12.
- The camera-laser-unit 1 can be easily and directly calibrated in any coordinate frame 19 (if the position of point of origin 0 of the frame 19 is

known in the global coordinate frame 13), without the need for time-consuming alignment processing.